SciDAC
Computational Astrophysics Consortium
Supernovae & GRB's

Where Theory Meets Observation

Peter Nugent

Lawrence Berkeley National Laboratory

Why Bother Studying Supernovae?

The DoE is very interested in them:

- Supernovae are responsible for almost all the elements in the universe beyond Helium
- They comprise the largest explosions in the universe of both the thermonuclear and core-collapse variety
- Fundamental in the study of particle physics (neutrinos, cosmic rays, etc.)
- Can be used to determine distances to 7% across the visible universe, thus key to measuring the acceleration history of the universe and dark energy!
- DoE is now involved in four major experiments in the next decade to study dark energy via supernovae: SN Factory, SNAP, LSST, DES….and btw we still don't know exactly how they explode or what their progenitors are.

Introduction to Spectrum Synthesis

Spectrum synthesis is the computation of a theoretical spectrum of a model atmosphere based upon the *known laws of physics*. The differences seen between various methods can be boiled down to two points:

- Which laws of physics you use, approximate or disregard
- What was the underlying model atmosphere

The goals of spectrum synthesis for supernovae are three-fold:

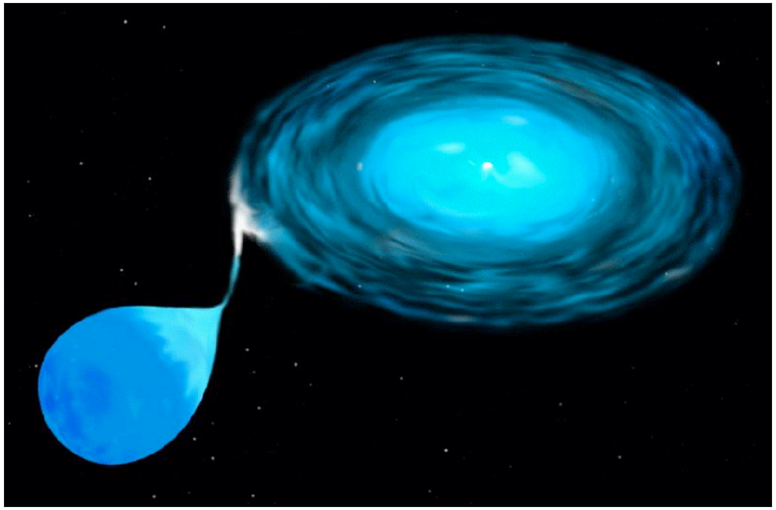
- Calculate the spectra of detailed explosion models, compare with observations and falsify or validate the models
- Calculate various "toy models" in order to predict or explain a set of observations
- Parameterize a model atmosphere and calculate the subsequent spectra, compare these directly to observation in order to measure nucleosynthesis products and luminosities (and hence the distance to the supernova).

At the end of the day spectrum synthesis is a high-end Vis product….

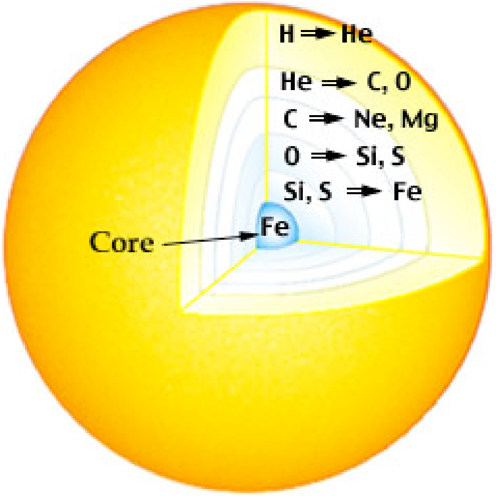
Supernovae Physics

Fundamentally there are two types of supernovae:

- **Thermonuclear - Type Ia**



- **Core Collapse - Type II (P,L,n) & I b/c**



Supernovae Classification

They are primarily classified based on spectroscopy near peak brightness and subsequently on their photometric evolution.

Hydrogen (Type II) / No Hydrogen (Type I)

Type IIP - Plateau lightcurve

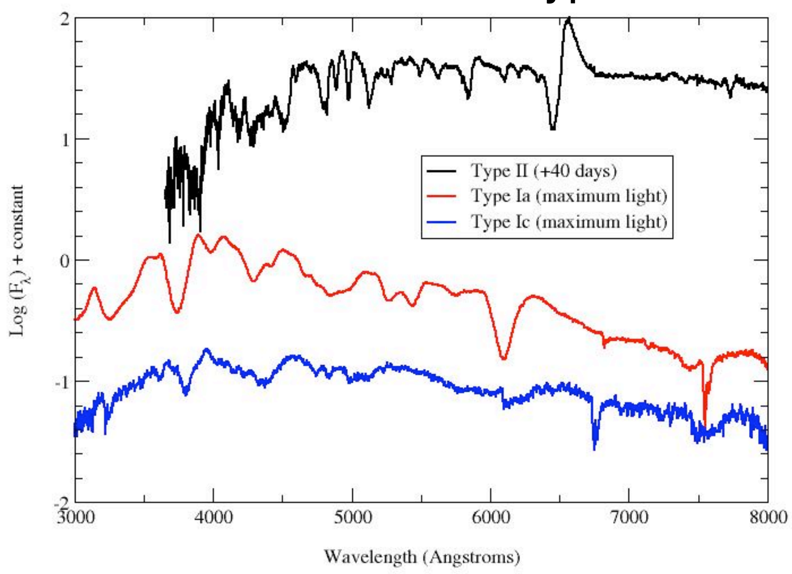
Type IIL - Linear lightcurve

Type IIn - narrow H lines

Type Ia - Strong Si II and S II lines

Type Ib - Weak Si II and He I lines

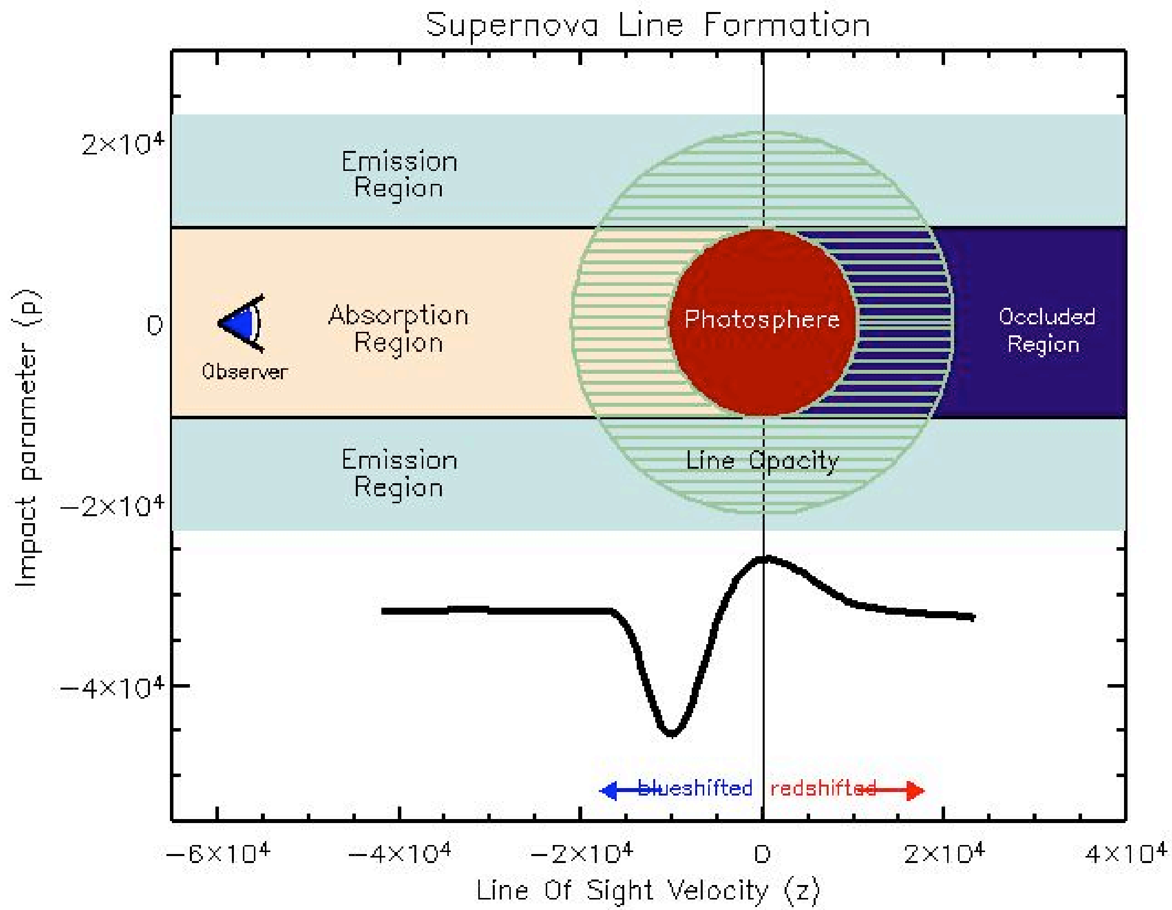
Type Ic - Weak Si II (GRB-SNe)



Supernova Spectra

Supernovae explode at velocities that are a significant fraction of the speed of light (0.05 - 0.20 c).

Their spectra are dominated by P-cygni line profiles, often complicated by the fact that many profiles lie on top of each other.



The Codes

We employ 3 different codes to study the spectra. Each has its advantages and disadvantages in the understanding of these objects. Most of the time it is a trade-off between dimensions+physics versus speed.

SYNOW/MADSYN - 1-D, Simplified Physics, Model Atmospheres
(very quick line identification & velocity determination)

SEDONA - 3-D, Simplified Physics, Model Atmospheres
(what effects geometry has on determining distances to SNe)

PHOENIX - 1-D, Full Physics, Spectrum Synthesis
(can we make SNe better for distances/cosmology)

PHOENIX

PHOENIX is a state-of-the-art spectrum synthesis code which is currently in 1-D. It treats all the applicable micro-physics appropriately and has been used to model supernovae of all types, the sun, novae, cool stars, red-giants, quasars and active galactic nuclei.

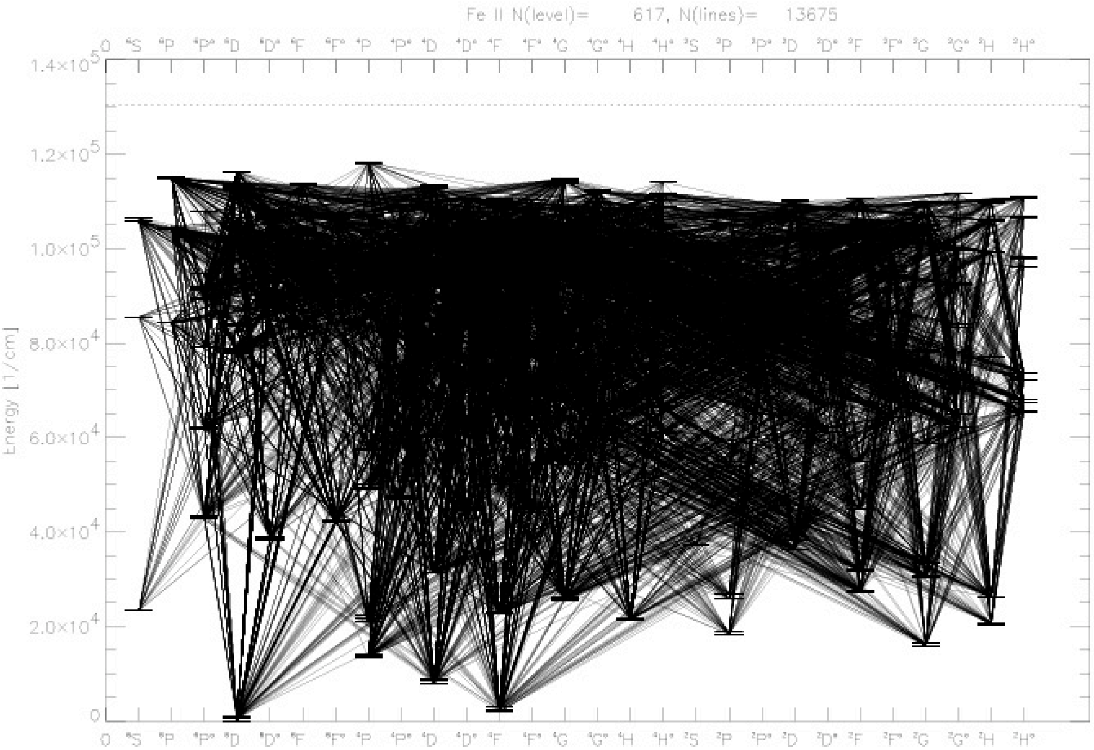
Input: Luminosity, Abundances, Density and Velocity Profiles and Non-Thermal Ionization from radioactive Ni, Co, etc.

Each of the above inputs range by an order of magnitude for SNe. 100 spatial zones, 300k wavelength points, energy conservation and non-LTE for 50 ionic species.

General Model Assumptions

- Full treatment of special relativistic radiative transfer in spherical geometry for all lines and continua,
- Radiative equilibrium in the Lagrangian frame (including all velocity terms),
- Full non-LTE treatment of most ions.
- Detailed profiles for the lines, fluorescence effects are included in the NLTE treatment
- Equation of state used includes up to 26 ionization stages of 40 elements as well as up to 206 molecules.

Atomic Data



Example Grotrian diagram for Fe II: 617 Levels - 1.2 million total lines

The level populations off all species are solved simultaneously as a very large set of linear equations, in *256-bit precision*!

This is due to the fact that there is a very large dynamic range in the level populations across ionization stages throughout the atmosphere.

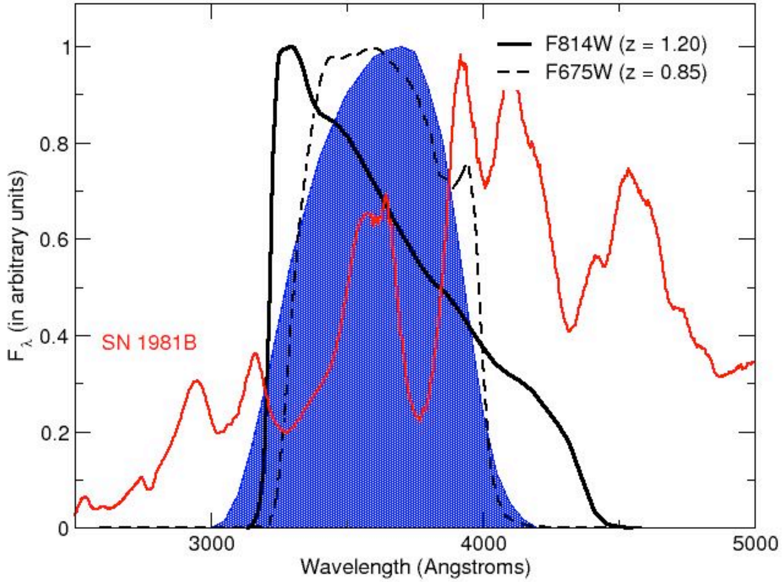
Population $\propto e^{-I/kT}$

All relevant b-f and f-f transitions are included - atomic line blanketing: about 2*10^6 lines dynamically selected from the Kurucz line list.

In order to implement this we have employed Super-LU + the quad-double packages developed by other members of CRD. Full runs on NERSC's IBM SP take ~ 1000 hrs.

Results: Spectral Templates

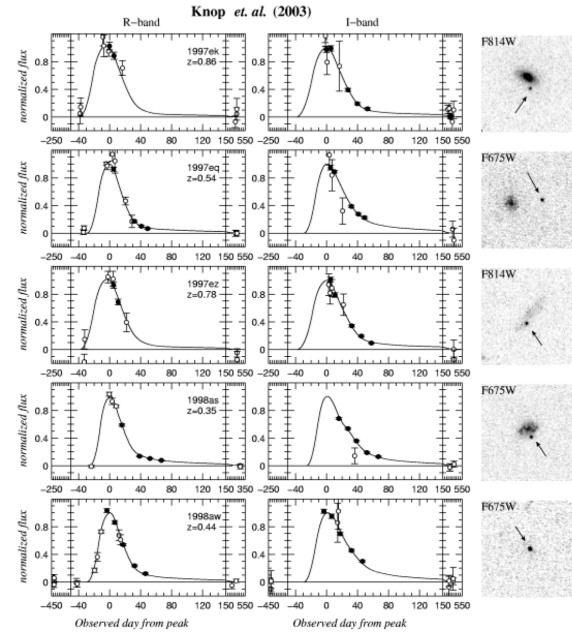
***K*-corrections - How we compare supernovae at different redshifts. Especially in the UV…**



The spectral templates were created by homogenizing IUE and HST observations + modeling to fill in the gaps.

Spectral Templates for Type Ia Cosmology…

Aphrodite (z~1.3) from the Riess *et al.* GOODs Very High-Z SN Search



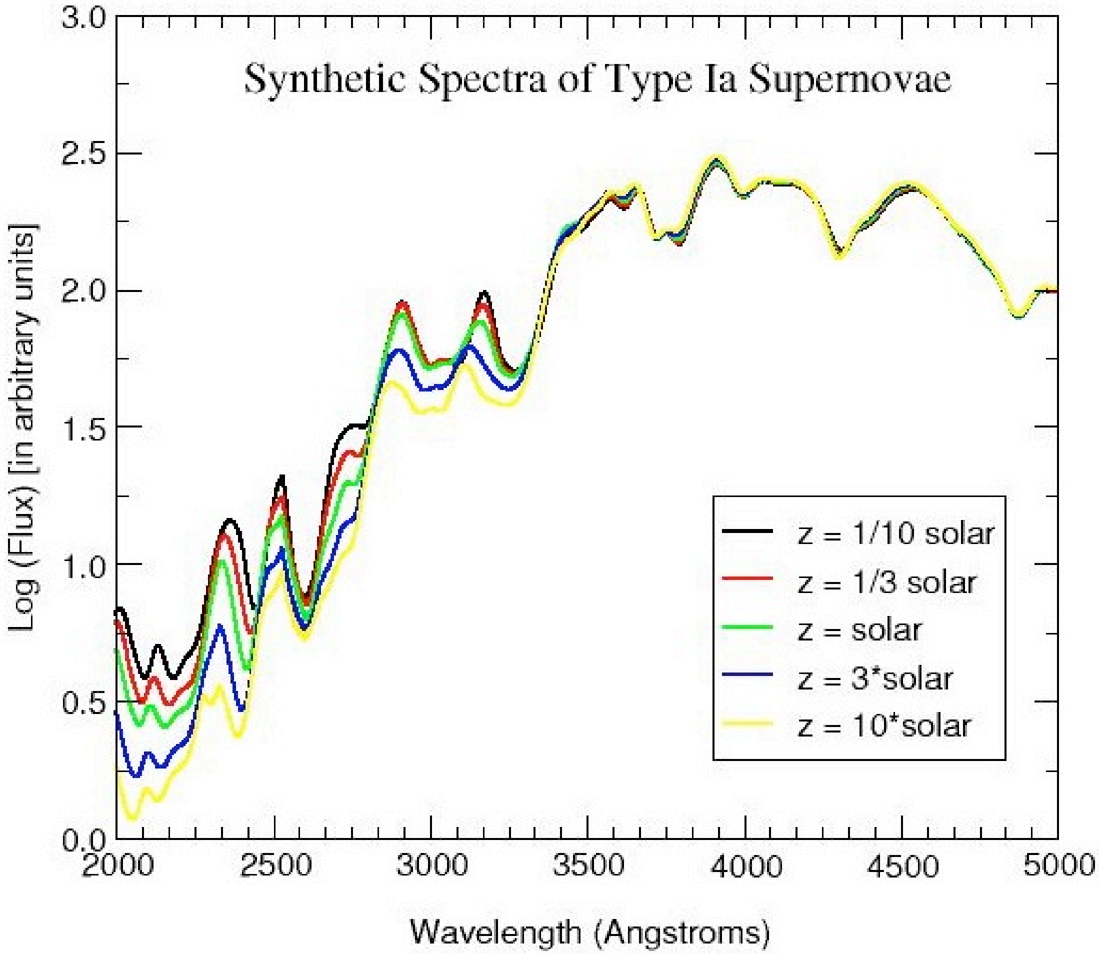
Precision measurements from Knop *et al.* HST data

SN 1997ff, still the highest redshift SN Ia observed to date from Riess, Nugent, *et al.*

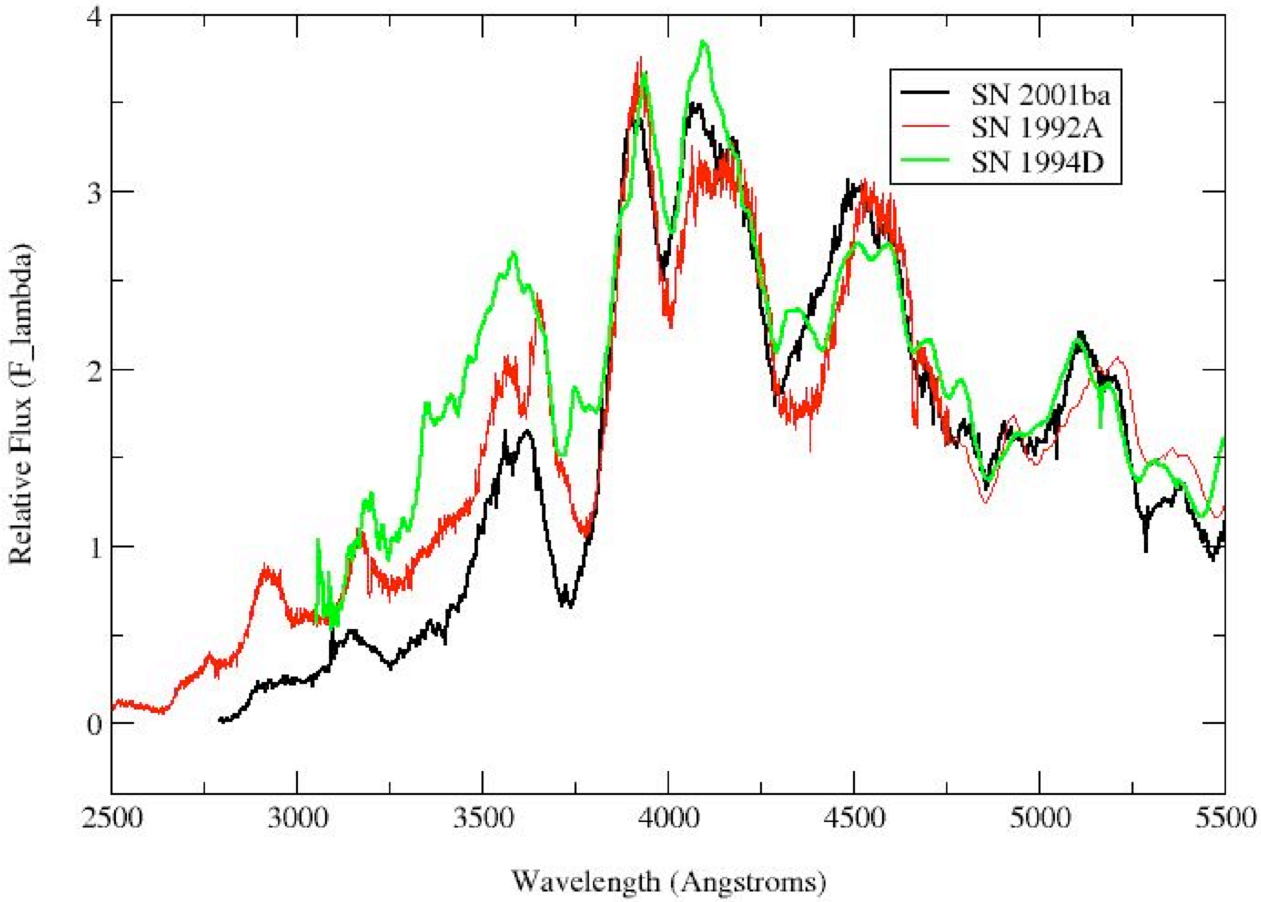
Type Ia Systematics - Metallicity

Synthetic spectra from Lentz *et al*., based on explosion models by Höflich *et al.*

Metallicity effects the UV.



Observed Metallicity….

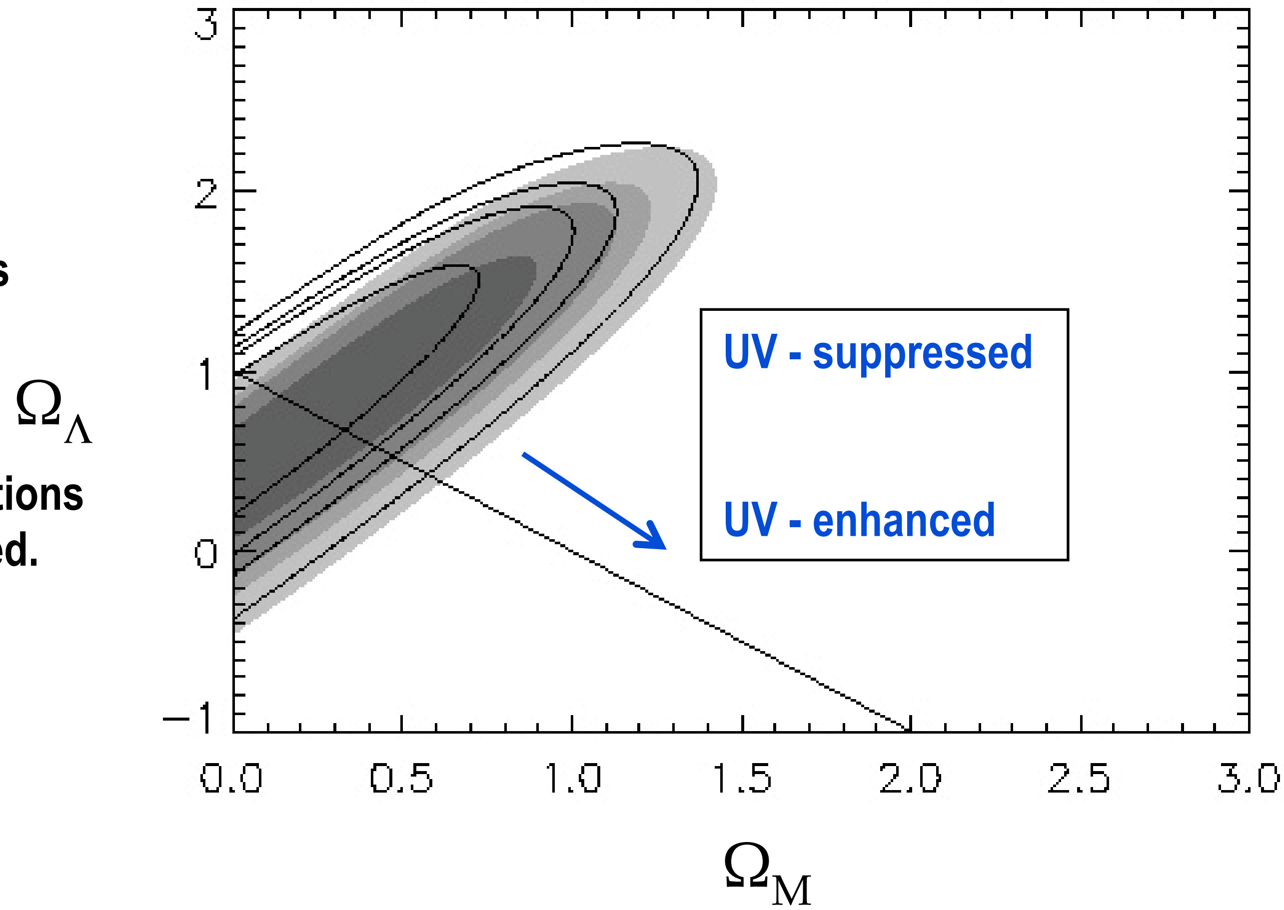


Nugent et al. HST/STIS studies of the UV…

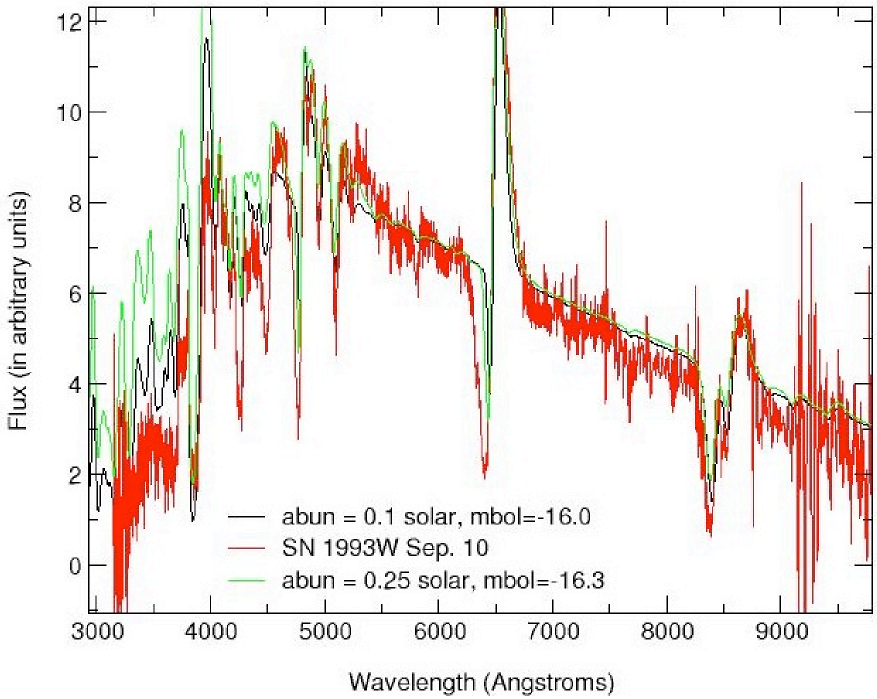
Metallicity and Cosmology

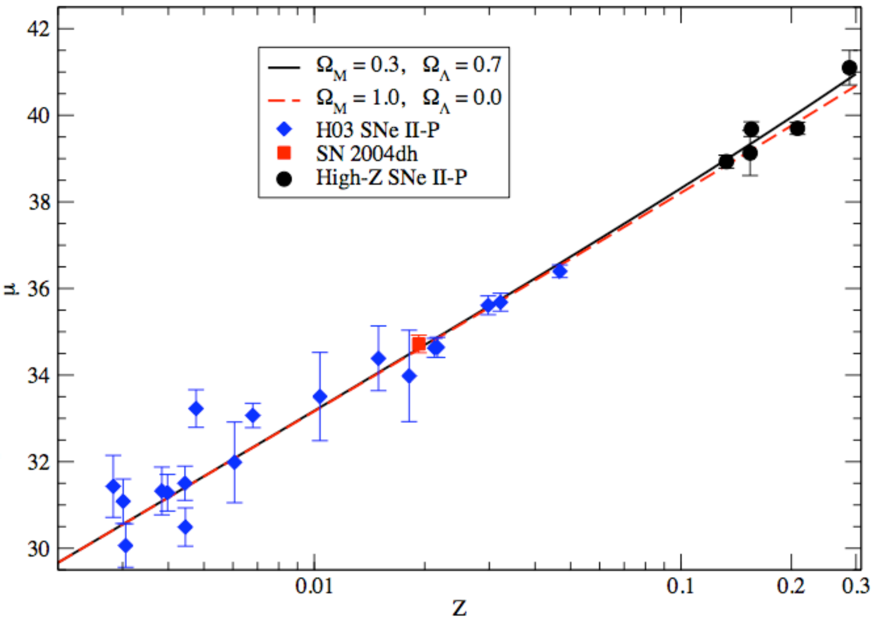
Understanding the UV has large implications for cosmology.

Intrinsic color and corrections for dust get intertwined.



Type IIP Supernovae and Cosmology





Detailed spectrum synthesis modeling has allowed us to determine a way to make the first Hubble diagram of Type IIP supernovae at high-redshift. These supernovae are found for "free" in rolling searches and provide a completely independent method for measuring the cosmological parameters.

SEDONA & 3-D Effects

SEDONA is a relatively simple code from the physics standpoint. A Monte Carlo code (follow the photons out) incorporating LTE and a 2-level atom. It iteratively solves for the temperature structure and calculates the polarization due to electron scattering and scattering off of lines.

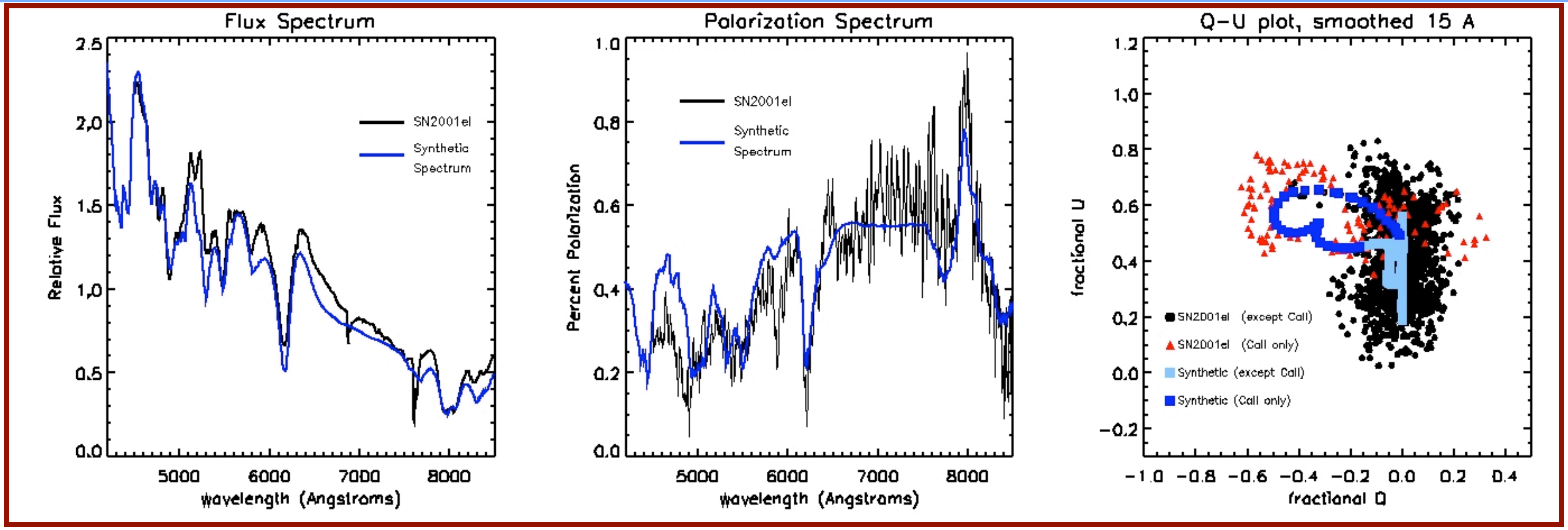
Developed to model the output of the previous SciDAC Supernova Programs.

Input: Luminosity, Abundances, Density and Velocity Profiles

300x300x300 spatial zones, 2-4k wavelength points, energy conservation and an atomic linelist of ~500k transitions.
10^{10} photons to converge in energy
10^{14} photons for spectropolarimetry

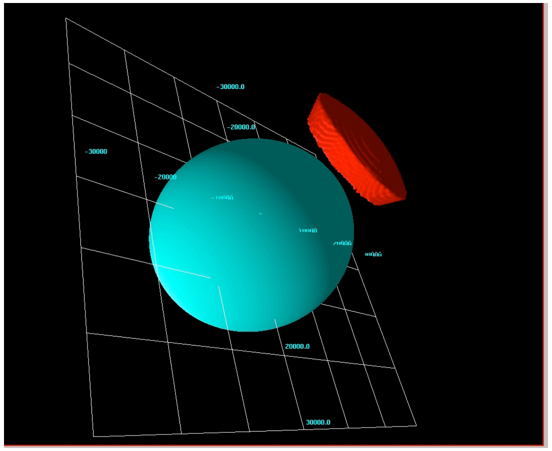
Full runs calculated on NERSC's IBM SP take ~50,000 hrs.

SEDONA for SN 2001el

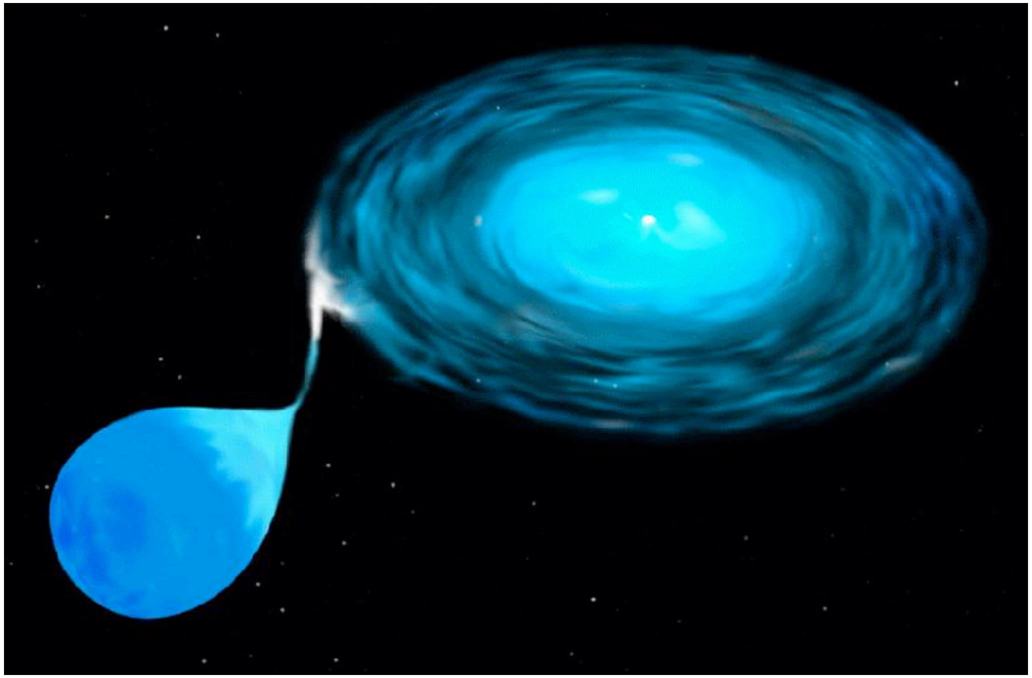


We need the large number of photons since:

- Polarization is low < 1%
- Atmosphere changes quickly on short scales (both in time and space)
- Many lines to interact with…



A Hole in Type Ia Supernovae?



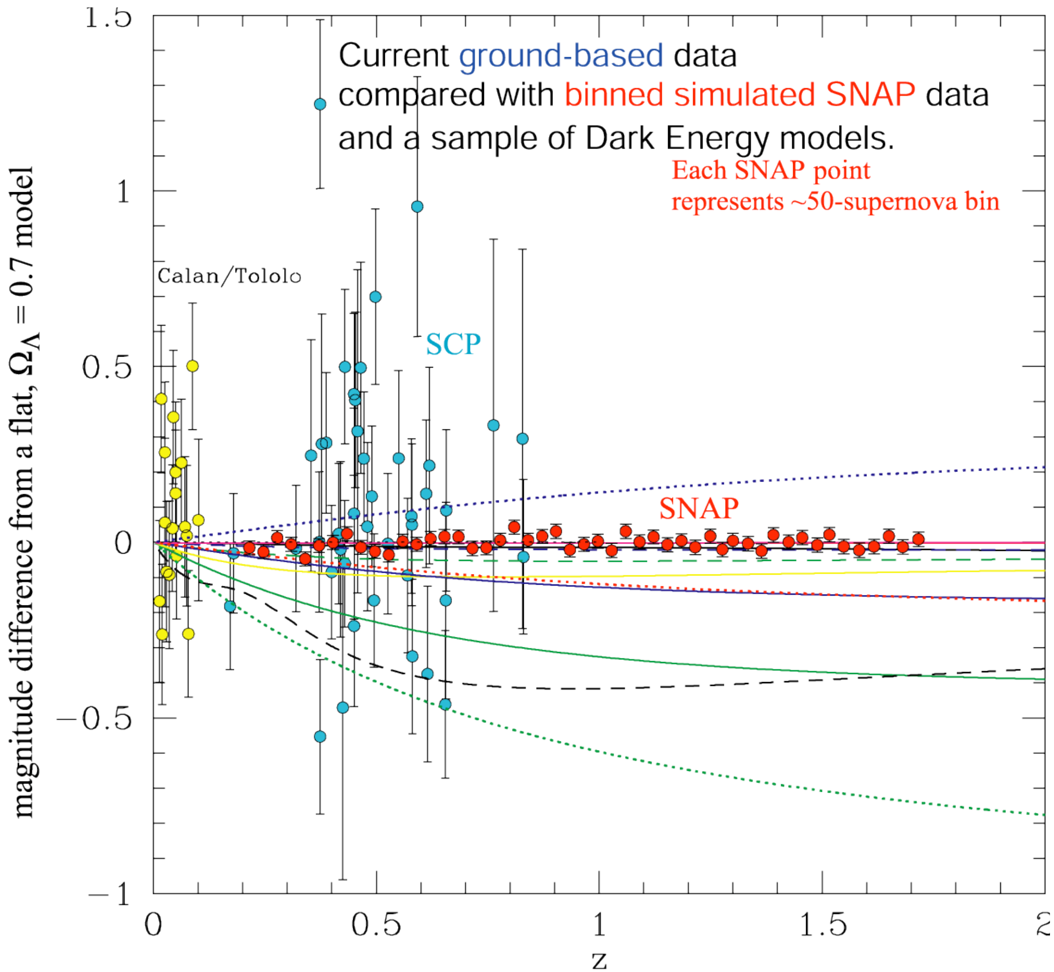
A White Dwarf accretes material from a companion star, either a main sequence Star or a Red Giant.

- The companion subtends an angle ~40^o.
- After explosion, the SN ejecta runs over the companion star in a few minutes to hours.
- This may leave a ~40^o hole in the SN ejecta . (Marietta *et. al.* 2000; c.f. Livne *et. al.* 1996)

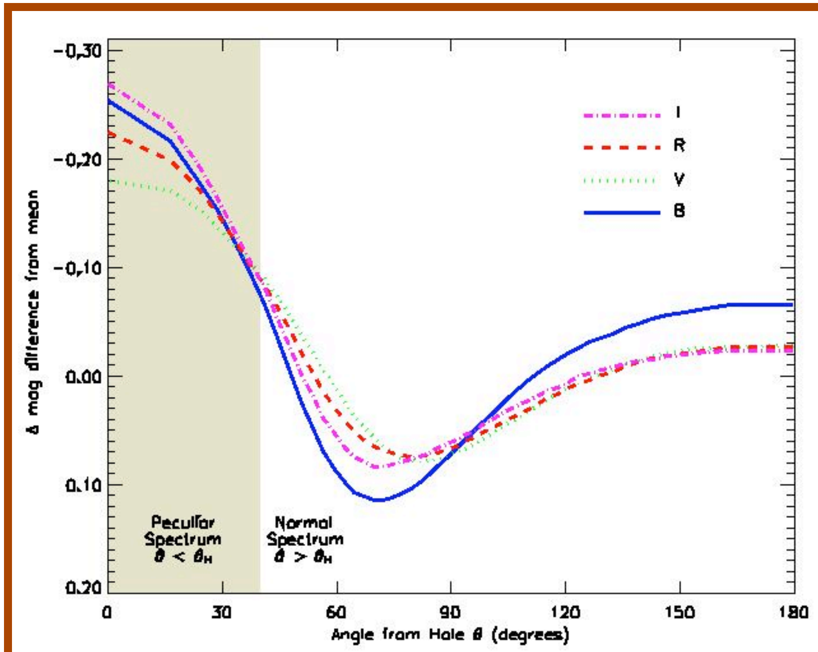
A Hole in Type Ia Supernovae?

SEDONA Model of SN Ia

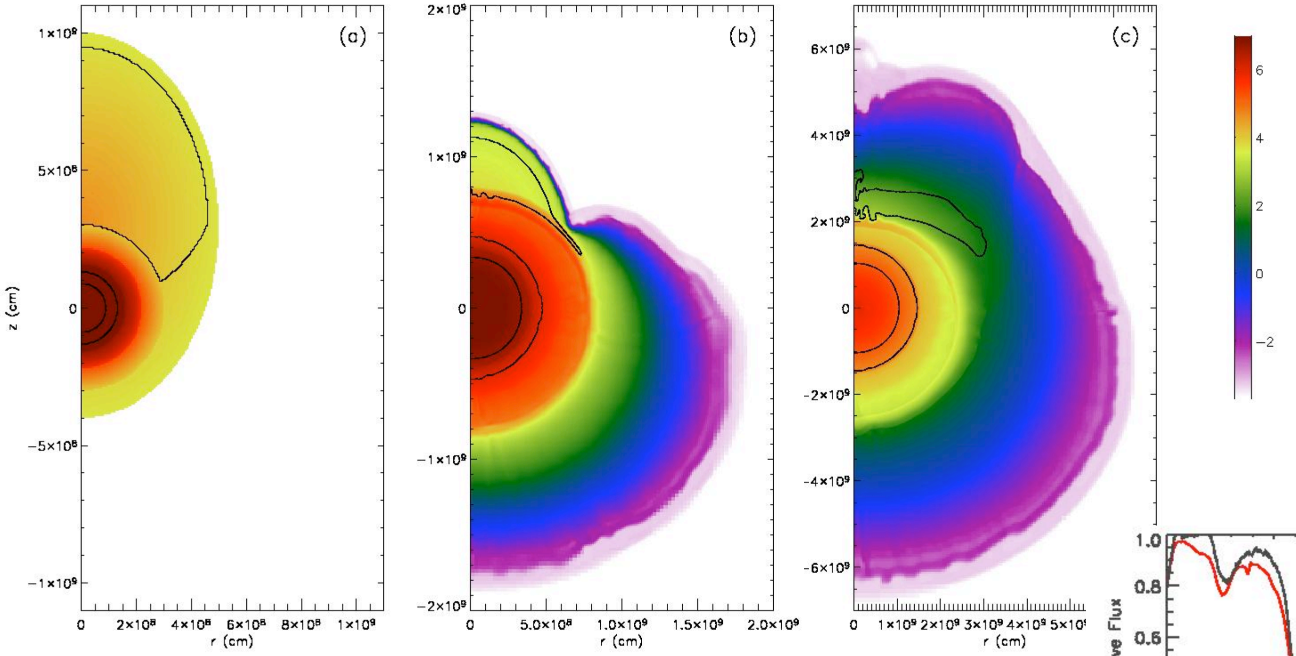
Effect on Cosmology?

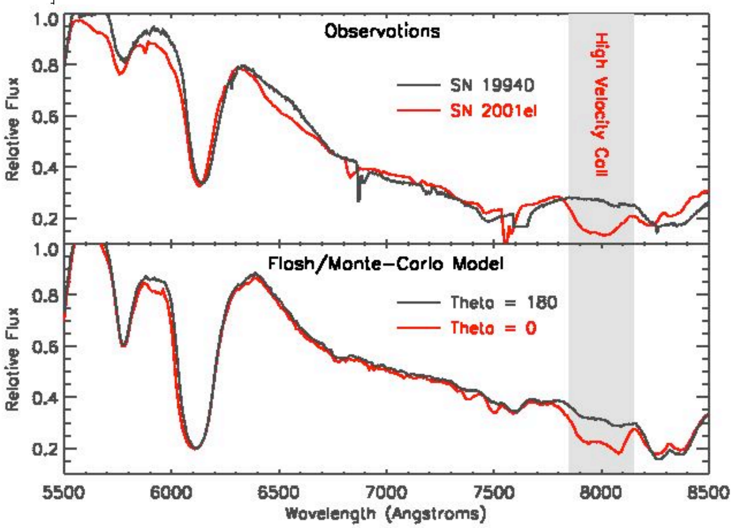


based on
Weller & Albrecht (2001)



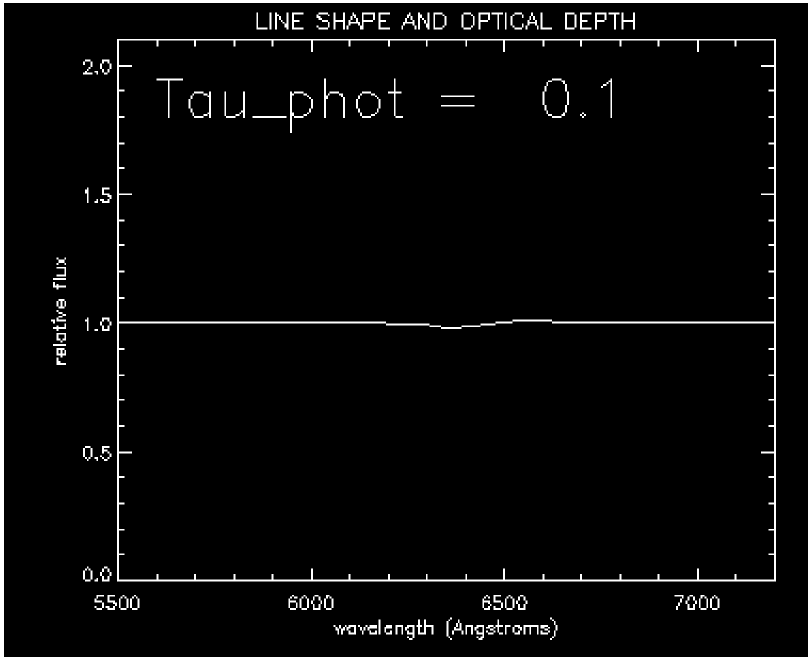
INCITE & Gravitationally Confined SN Ia Detonations





The spectrum synthesis of the Incite model compares favorably to observations and may be the first explosion model which "naturally" explains the transition from deflagration to detonation in thermonuclear supernovae.

SYNOW/MADSYN



Input for the photosphere:

- **Temperature**
- **Velocity**
- **Density (exp or pwr law)**

Input for the lines:

- **Optical depth**
- **Min and Max velocity**
- **T_{eff}**

SYNOW employs the Sobolev approximation for the line transfer, as well as a "hard" photosphere and equivalent 2-level atoms in LTE.

Highly parameterized and very fast.
Runs in < 10 sec, almost all time is spent reading Kurucz linelist.

Real-Time Assessment of Data for SN Factory/SNAP

Joins the expertise in optimization research with that of spectrum synthesis.

Makes it possible to”objectively” fit a spectrum and determine the parameters of the model atmosphere and their uncertainties.

Conclusions

- Many great nearby & high-redshift programs underway now
 --- All will rely on computational modeling to improve our understanding of supernovae and to constrain systematics.

- The CAC is exploring the explosion mechanisms of supernovae --- 3-D spectrum synthesis will be the only way to confront these calculations with observation.

- Understanding/Constraining 3-D effects will be important for "precision" cosmology --- all future SNe experiments

- We need much better methods than the Chi-by-eye used now to compare and contrast models with observation via spectrum synthesis

Conclusions (continued…)

The data coming from both the observations and the models are quite large…

Tb's for the hydro explosion models, which are input for the spectrum synthesis models, which then produce Mb's of data at each time-step for 100 days.